Dielectric Resonator Nano-Antennas: A Pathway to Efficient Optical Antennas

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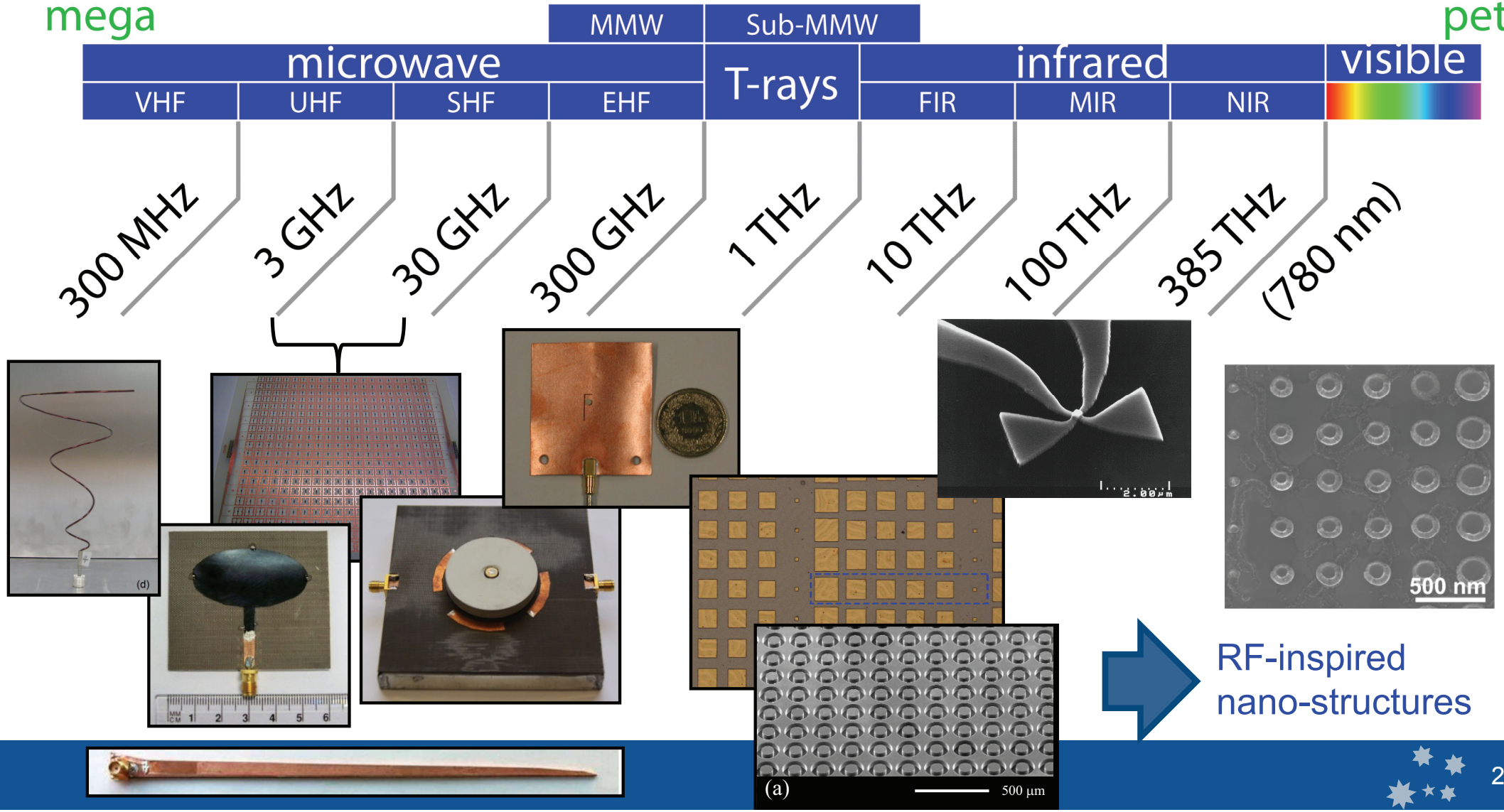
Functional Materials and
Microsystems Research Group

RMIT UNIVERSITY

Applied Electromagnetics Group in Adelaide: Antennas and FSS across the spectrum



Outline

1 Introduction

2 Scaling of Dielectric Resonators Antennas

3 Reflectarray of Optical DRAs: Design and experiment

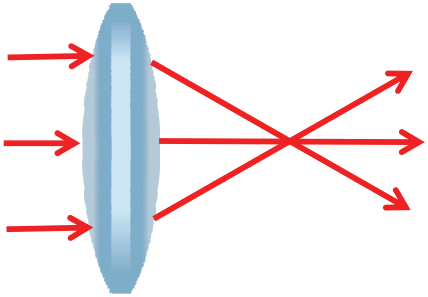
4 Conclusion

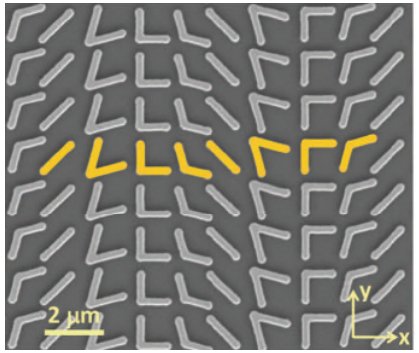
Manipulating light at sub-wavelength scale: Optical antennas

Enhancing the **efficiency**
And/or **resolution** for

- sensing
- spectroscopy
- light emission
- photodetection
- on-chip communication
- **optical components**

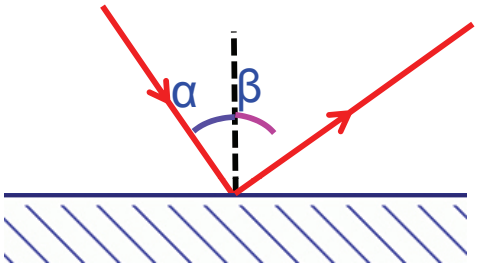
Flat Lenses



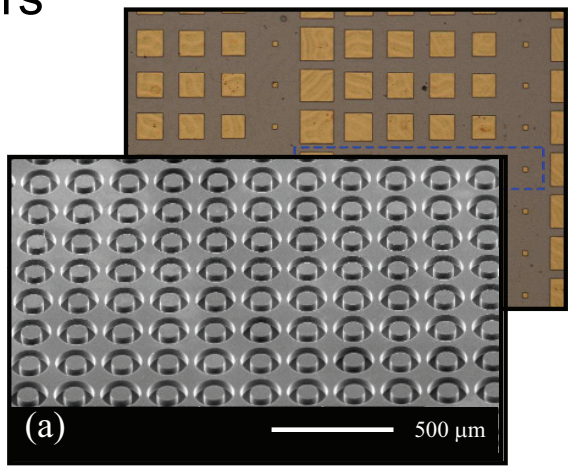


Yu et al., Science
334, 333 (2011)

"Anomalous" Reflectors



Niu et al., Opt. Express
21(3), 2875 (2013)

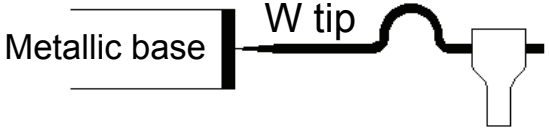


Withayachumnankul et al.,
Adv. Opt. Mat 1, 443 (2013)

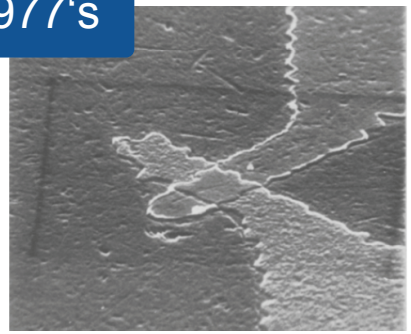
Optical antennas: 1970's to today

1970's

e.g. A. Javan's group, MIT

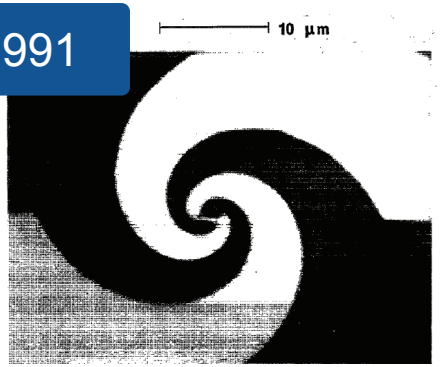


1977's



by E. Wiesendanger, F. Kneubühl, Appl. Phys. 13(4) (1977)

1991

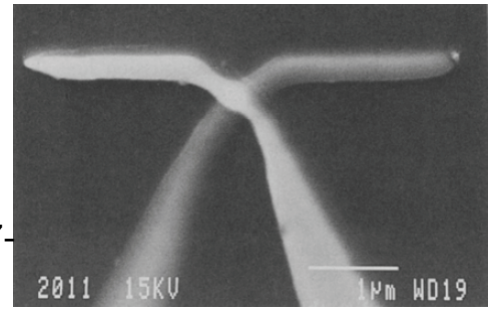


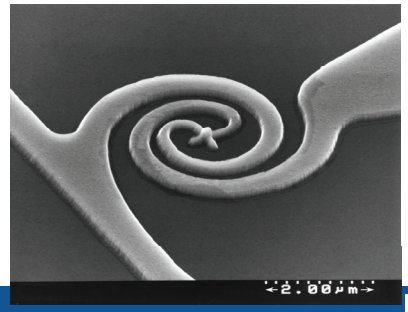
Grossman et al. (NIST) Appl. Phys. Lett. 59 (25) (1991)

10 μm

1990's

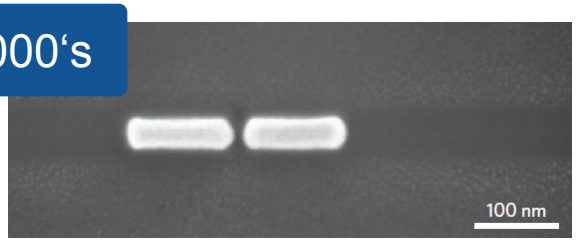
Wilke et al. (ETHZ) Appl. Phys. B 58, 87-95 (1994)





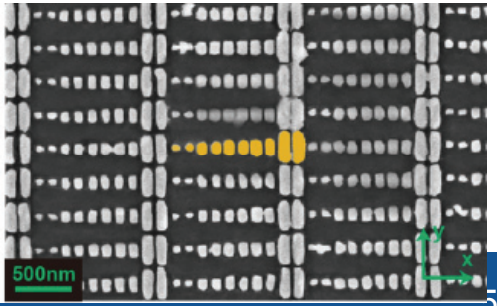
Fumeaux et al. (ETHZ, CREOL)Appl. Phys. B 63 (1996)

2000's



"Antennas for light", Novotny & van Hulst, Nature Photonics 5, 83–90 (2011)

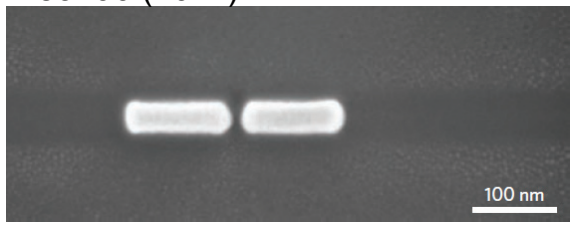
Sun et al., Nano Lett. 12, 6223 (2012)



Current research on optical antennas

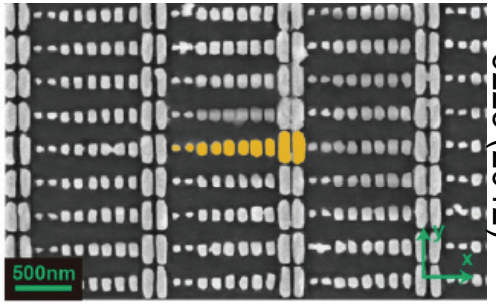
Conventional optical antenna structure:
→ Resonant metallic antenna on top of dielectric

"Antennas for light", Novotny & van Hulst, Nature Photonics 5, 83–90 (2011)



1. Fabrication accuracies down to a few nanometres

Current fabrication methods { Focused ion beam milling
Electron beam lithography

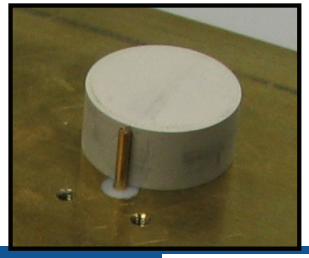


Sun et al., Nano Lett. 12, 6223 (2012)

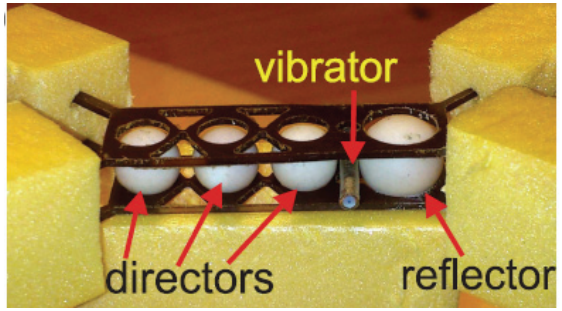
2. High Ohmic loss of metal at optical frequencies

The optical antenna research mostly focuses on metallic nanostructures (plamonics)

One possible solutions for higher efficiency:
Optical dielectric resonator antenna



Scale down
200,000 times!

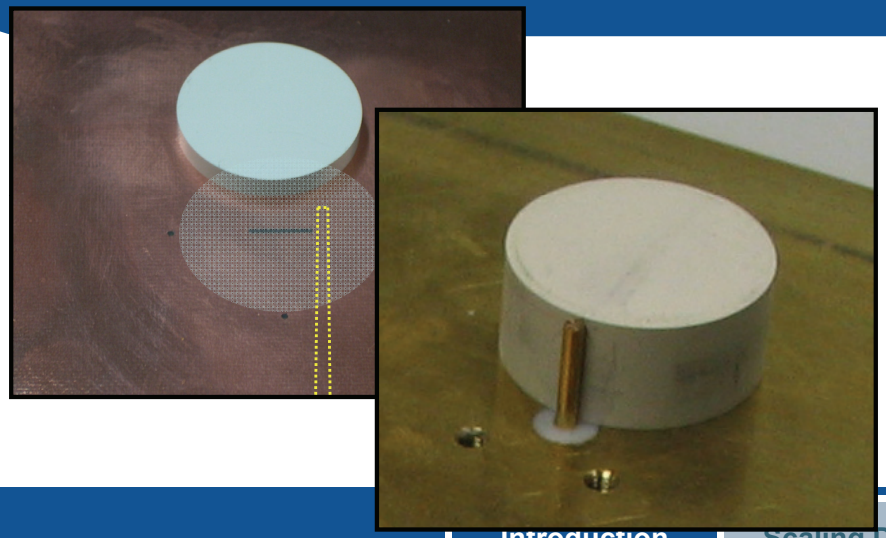


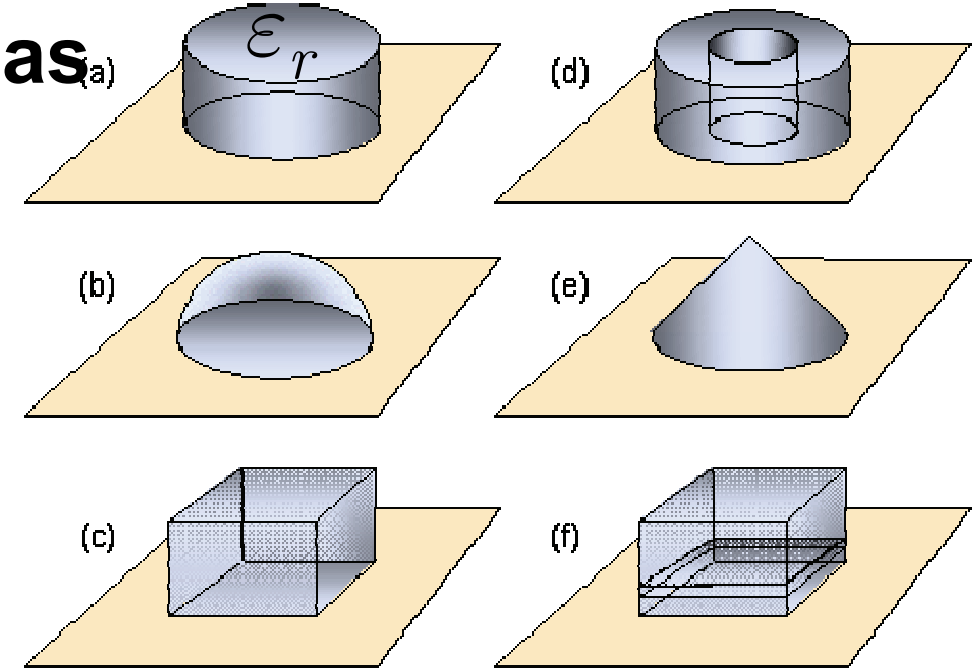
Filonov et al., Appl. Phys. Lett. 100, 201113 (2012)

Dielectric Resonator Antennas

Dielectric resonator antennas

- Dielectric resonator in open environment
- Low-order resonant modes have low radiation Q factor
  → good radiators!
- Introduced by Long et al. (1983)





Characteristics of DRA

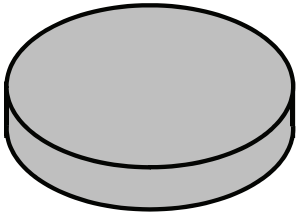
- Small size ($\varepsilon_r \approx 10$ typically)
- Larger bandwidth than patch
- High efficiency
- Versatility
- Simplicity of excitation

Fundamental cylindrical DR modes

TE: transverse electric

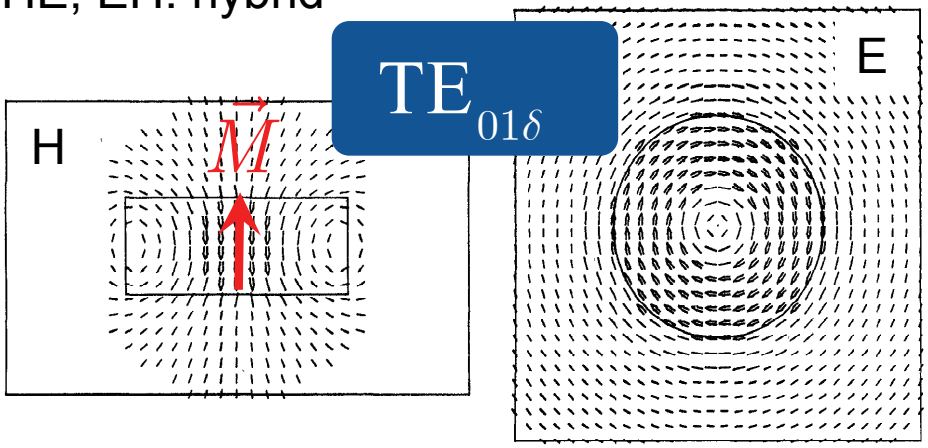
TM: transverse magnetic

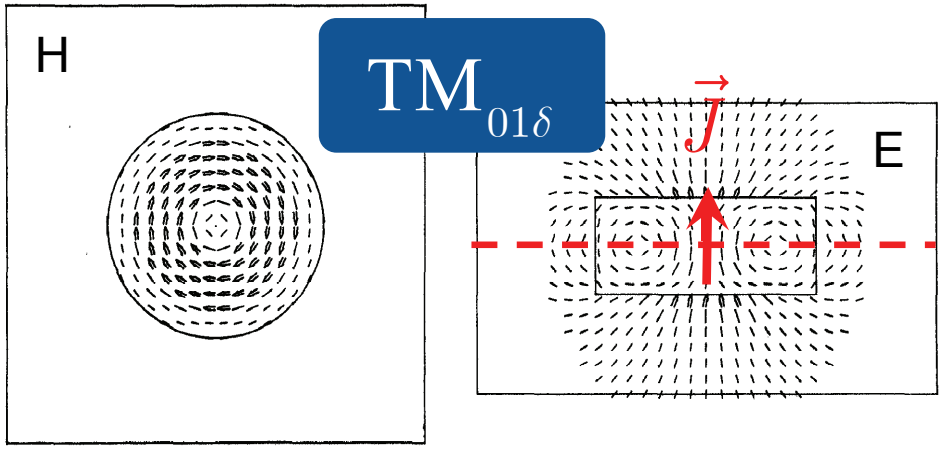
HE, EH: hybrid

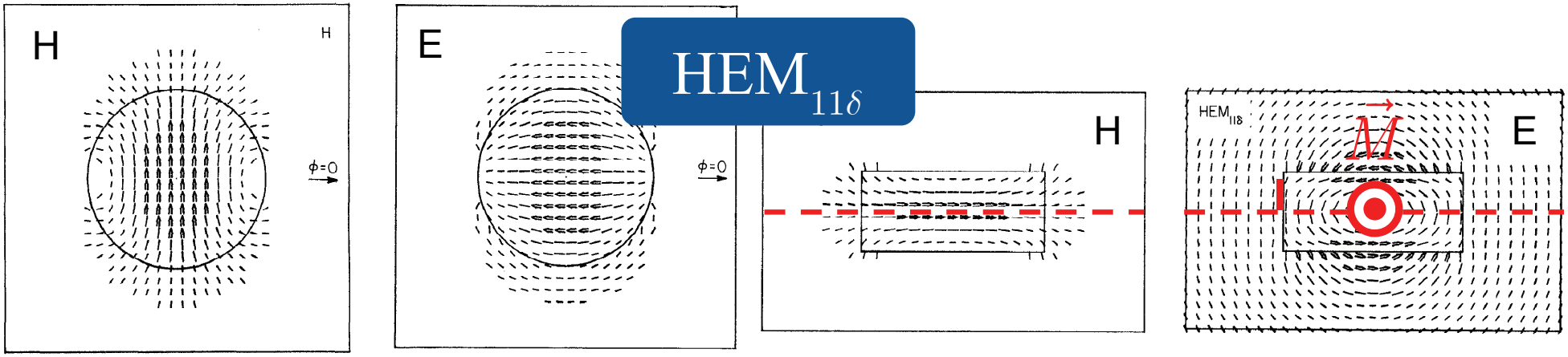


Modes index $m\ n\ l+\delta$

Φ ρ z

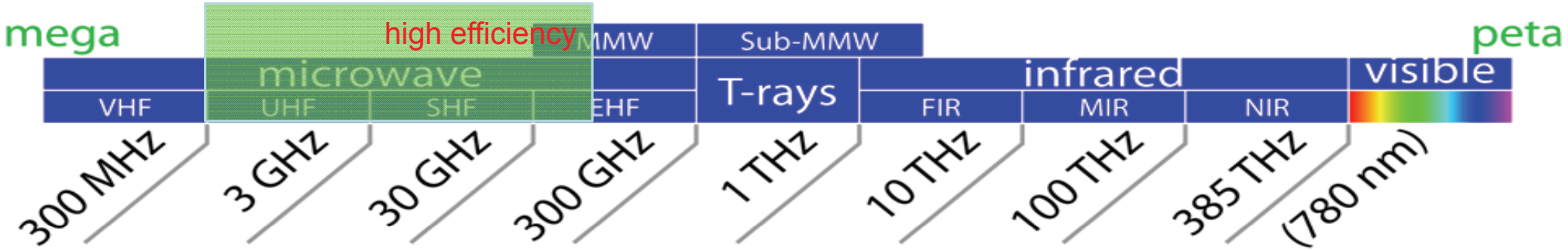




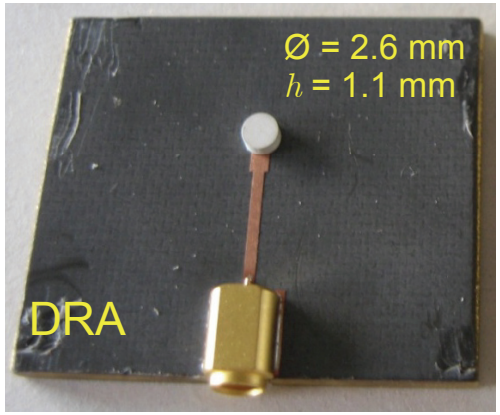


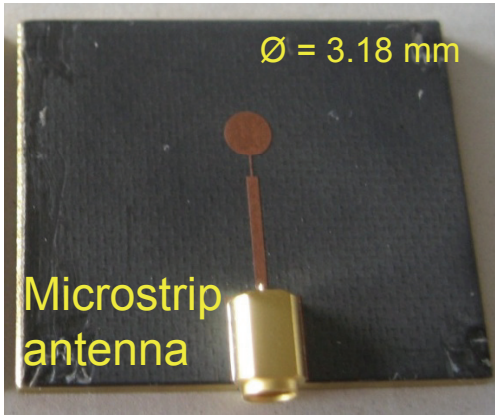
From: Kajfez, Glisson & James, MTT-32(12), 1609ff (1984)

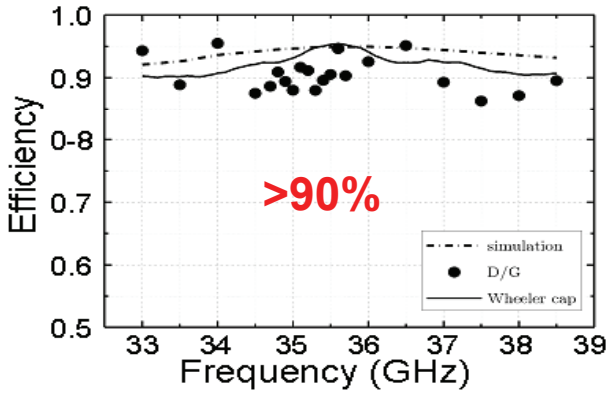
High efficiency DRA at MMW

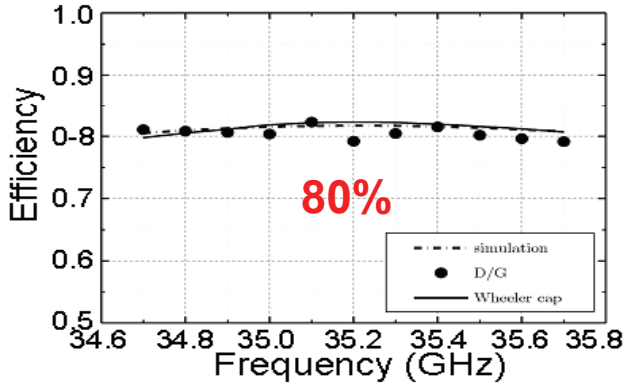


36 GHz



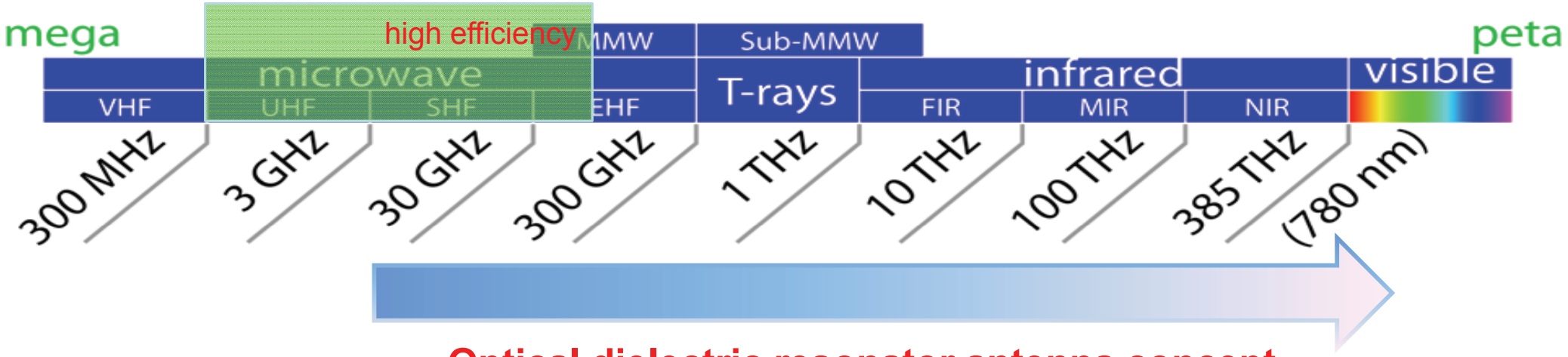






Lai et al., T-AP 56(11), 3589 (2008)

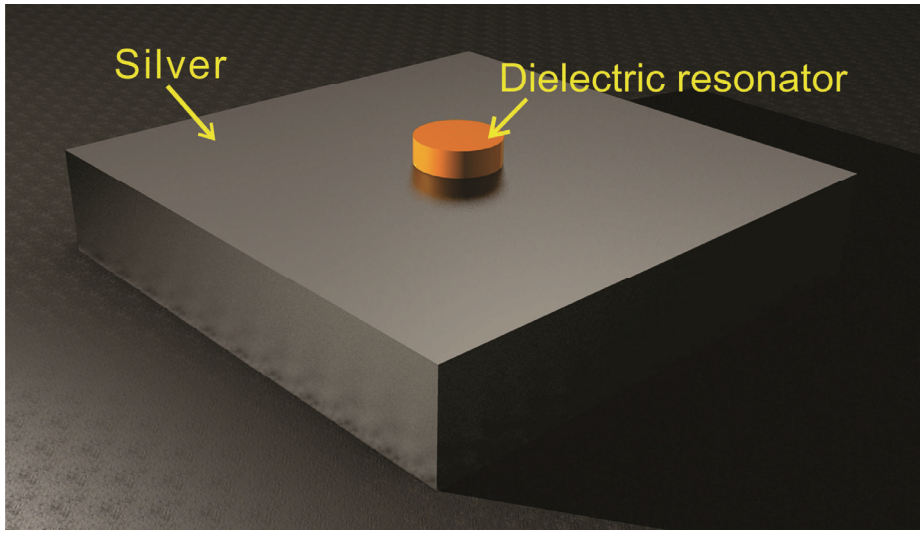
Towards experimental demonstration of optical DRA



Optical dielectric resonator antenna concept

Optical antenna structure:
Resonant dielectric on top of metal

Aim:
Reduce metallic losses in
RF-inspired nano-antennas
→ Dielectric resonator optical antenna



Outline

1 Introduction

2 **Scaling of Dielectric Resonators Antennas**

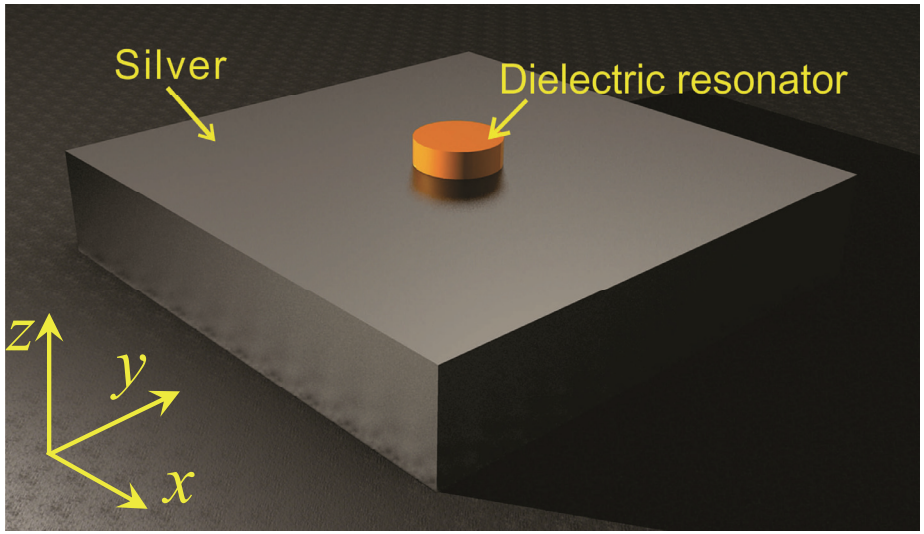
3 Reflectarray of Optical DRAs: Design and experiment

4 Conclusion

Frequency & Material selection

Target frequency:
HeNe red laser (λ = 633 nm)

Materials:
Close collaboration
with nano-fabrication team



THE UNIVERSITY of ADELAIDE
RMIT UNIVERSITY

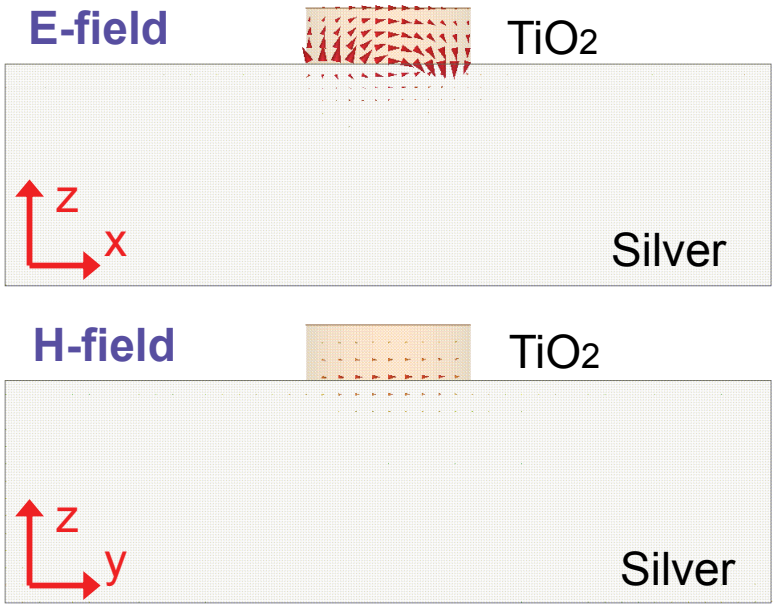
Chosen dielectric resonator material:
TiO2 with thickness **50 nm**

Relative permittivity of
- 8.29 in X and Y direction
- 6.71 in Z direction

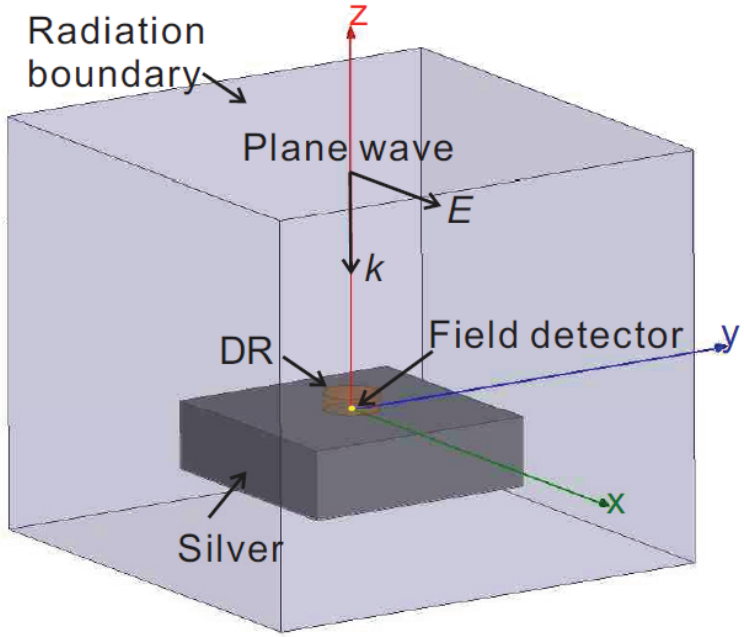
Silver permittivity −16.05+*j*0.57 at 474 THz (calculated from the Drude model)

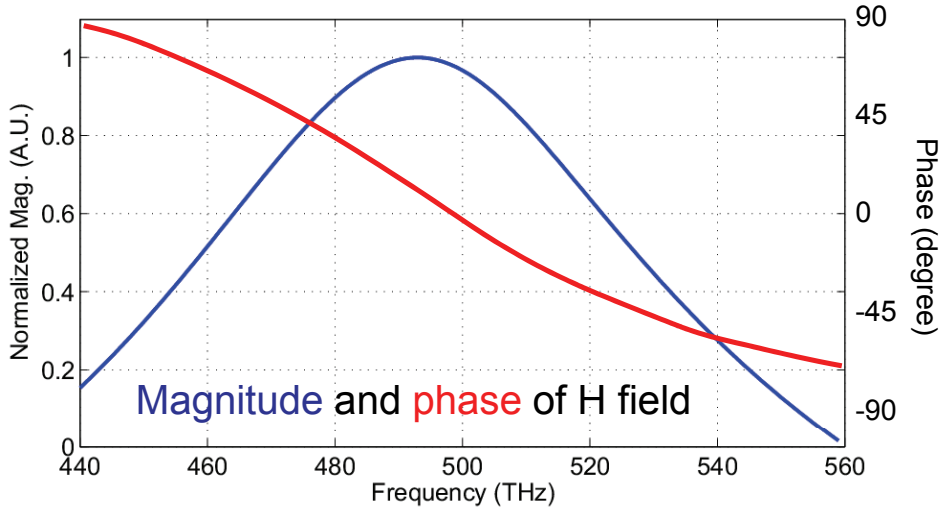
Scaled model of DRA

Plane wave excitation
→Fundamental HEM 11δ mode
→ Find resonance by varying radius

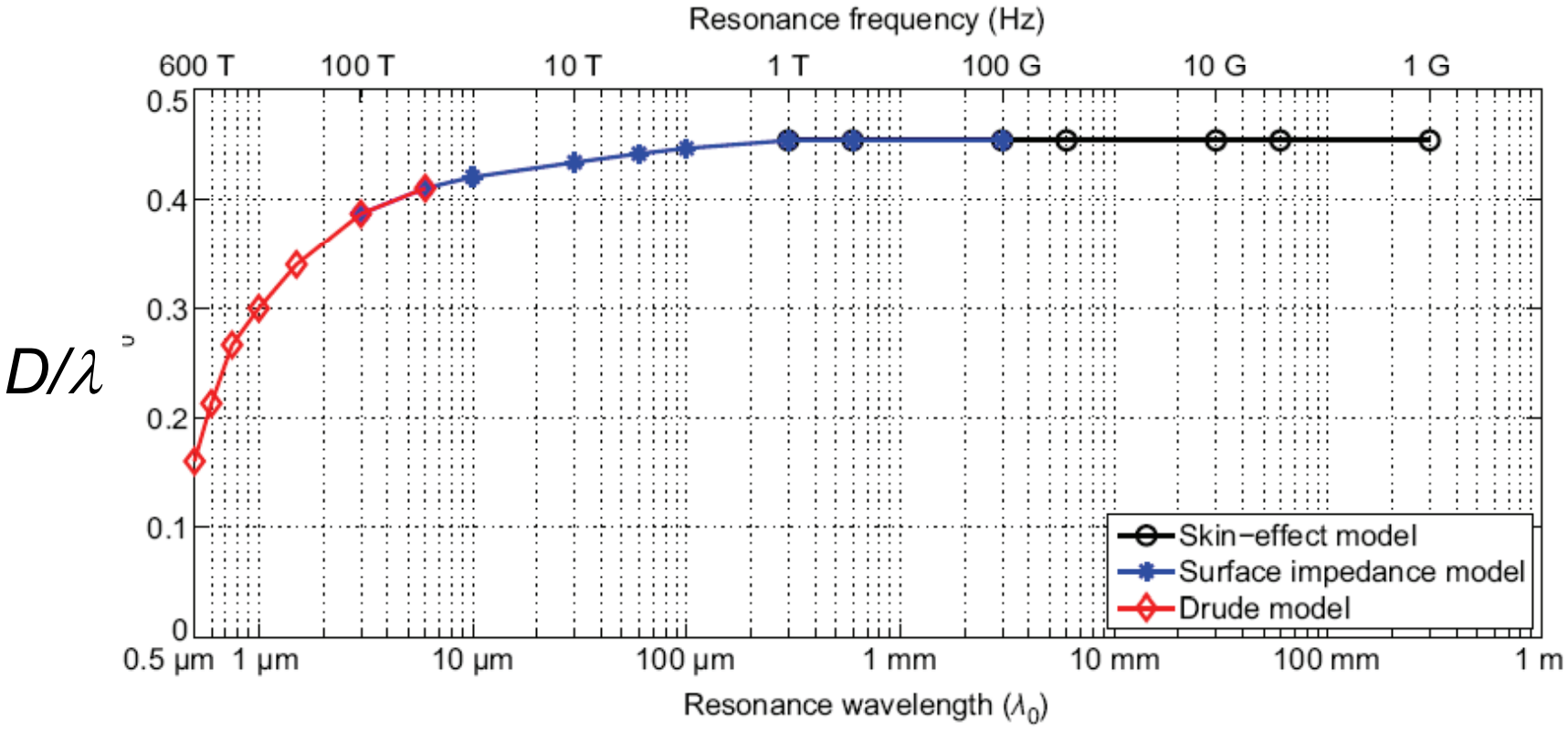


HEM11δ mode field distributions

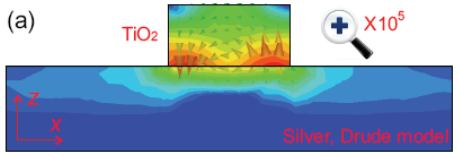




Scaling from Microwave to Optical frequencies

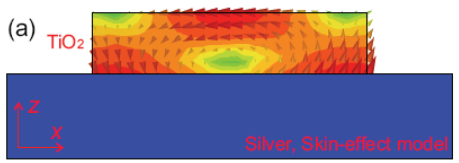


Significant Plasmonic effects!



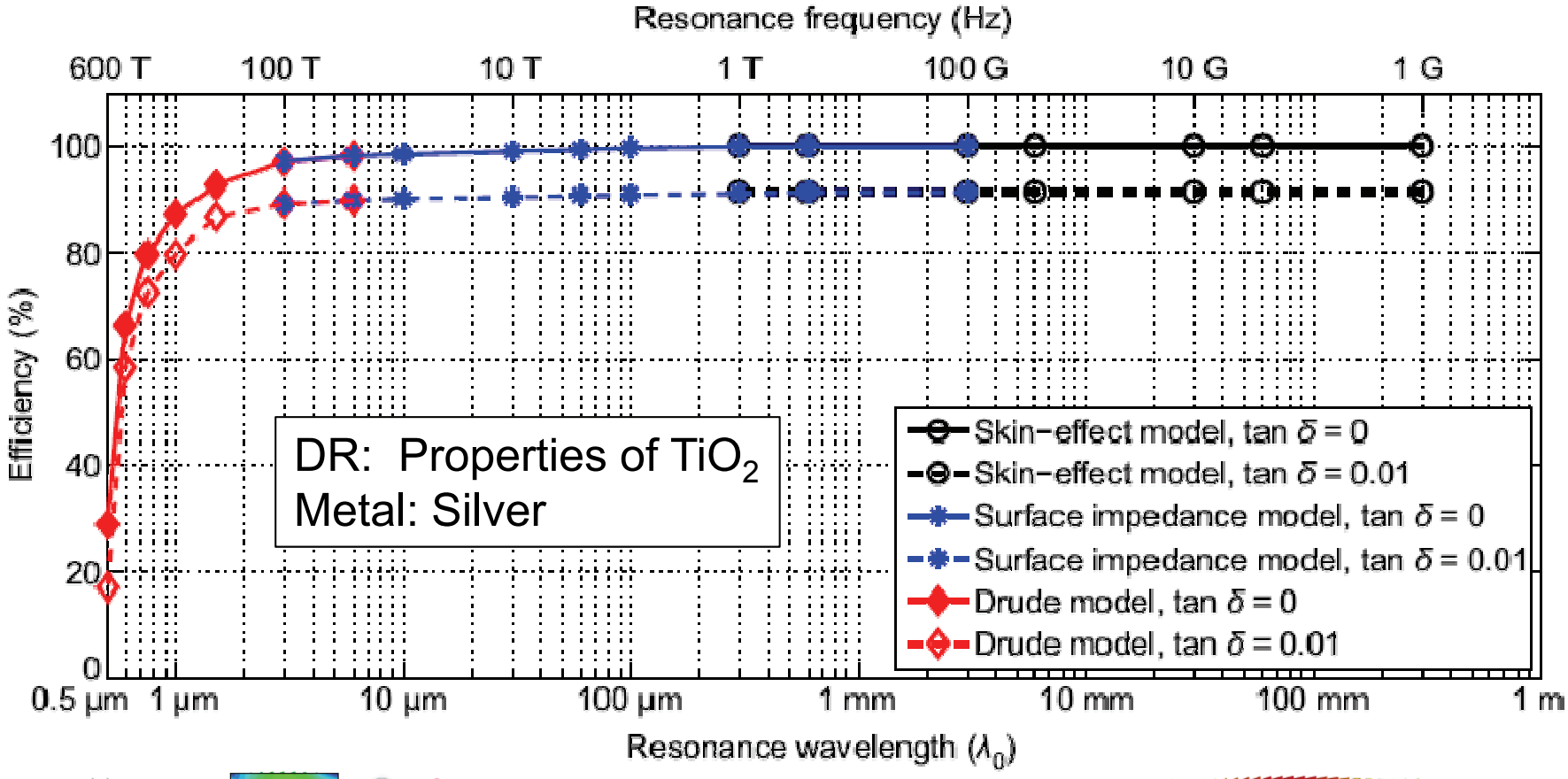
500 THz

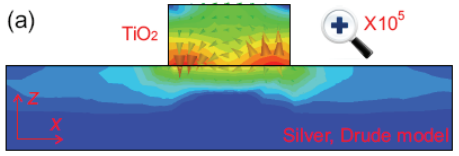
X10^{-5}



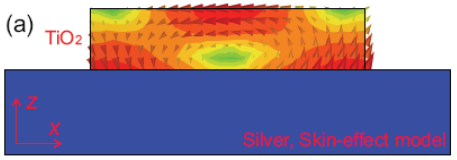
5 GHz

Efficiency: from microwaves to visible frequencies





X10^{-5}



500 THz

5 GHz

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3 **Reflectarray of Optical DRAs: Design and experiment**

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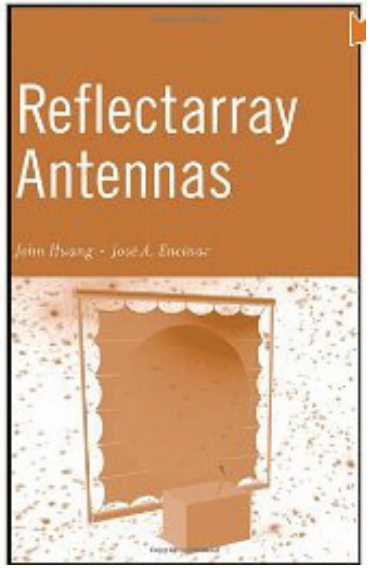
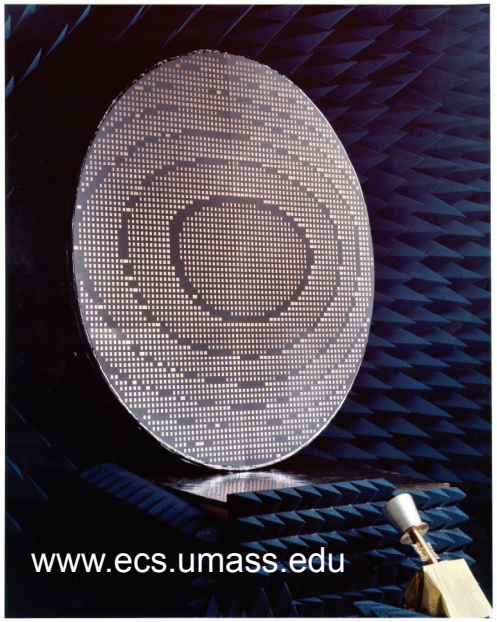
Optical reflectarrays…

Reflectarrays (→ equivalence principle)

- Dates back from the 1960's
- Relatively mature techniques
- Sophisticated realizations
- Scalable to optical frequencies





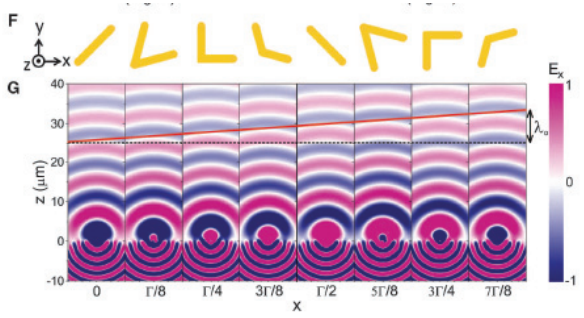
Vs

Meta-surfaces (→ Generalized Snell's law)

Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction

Nanfang Yu,[1] Patrice Genevet,[1,2] Mikhail A. Kats,[1] Francesco Aieta,[1,3] Jean-Philippe Tetienne,[1,4] Federico Capasso,[1]* Zeno Gaburro[1,5]*

SCIENCE VOL 334 21 OCTOBER 2011

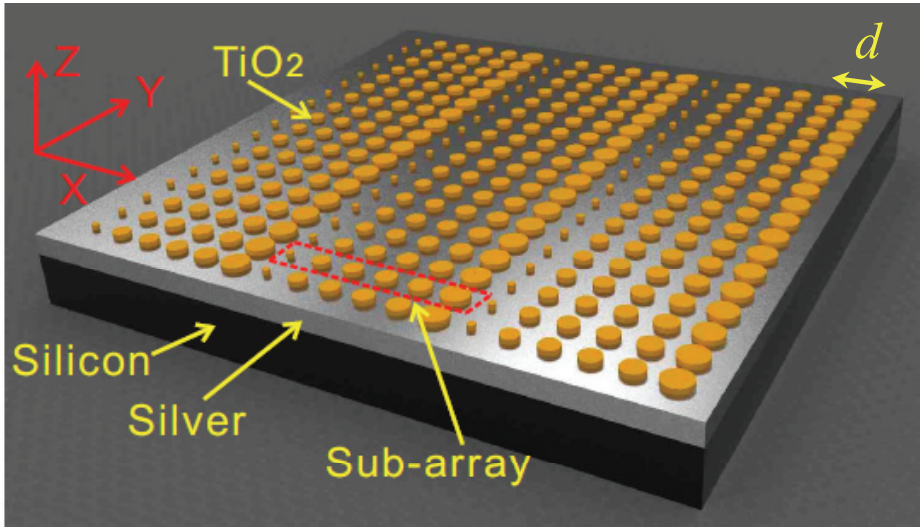


Different approaches and languages

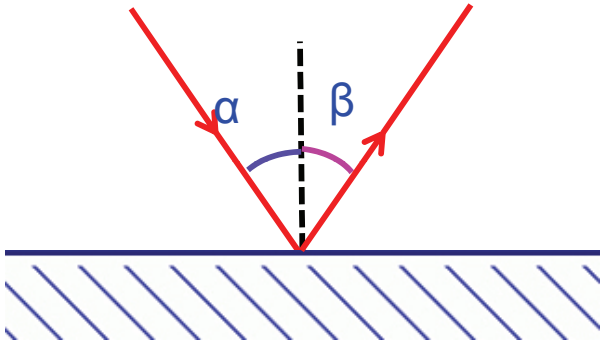
Optical reflectarray of dielectric resonator antennas

Experimental demonstration using simple reflectarray
→ „Gradient meta-surface“

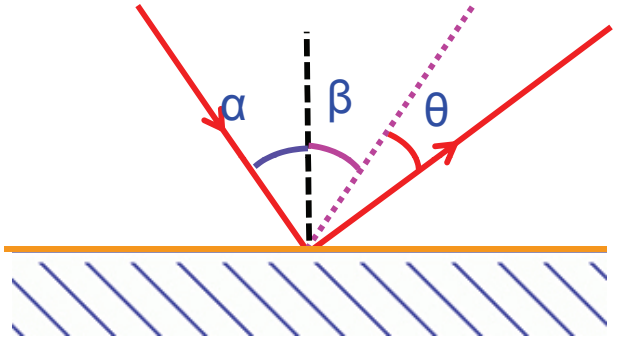
Introduce progressive phase ϕ through variation DR radius



6-element reflectarray



Mirror



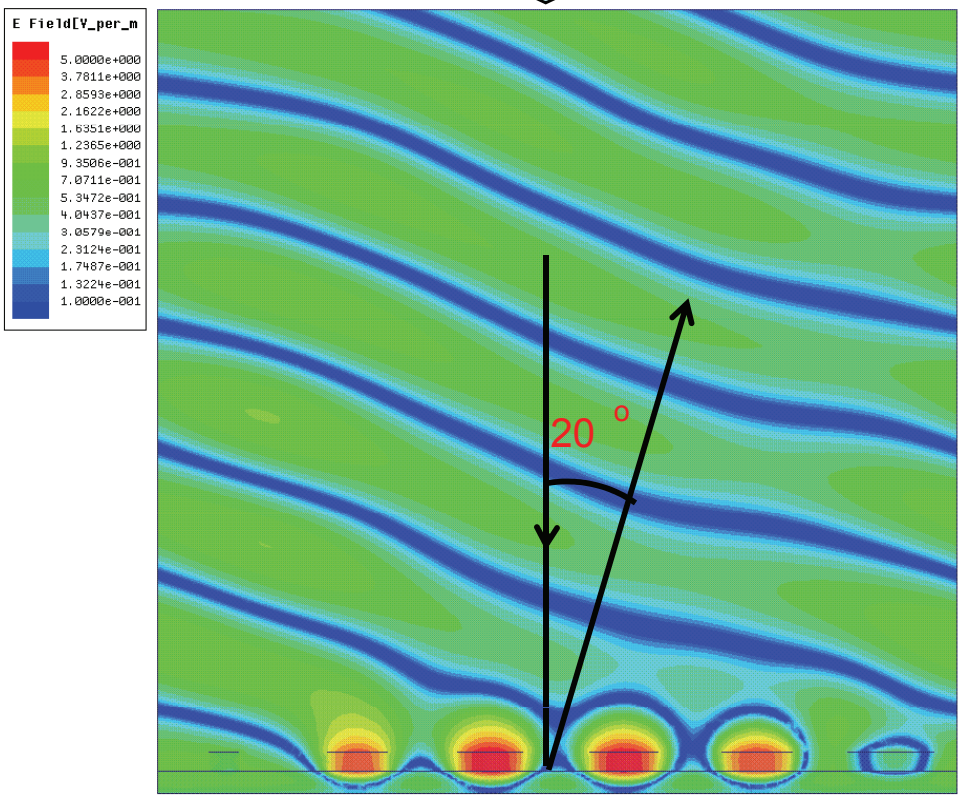
Reflectarray

Deflection angle θ

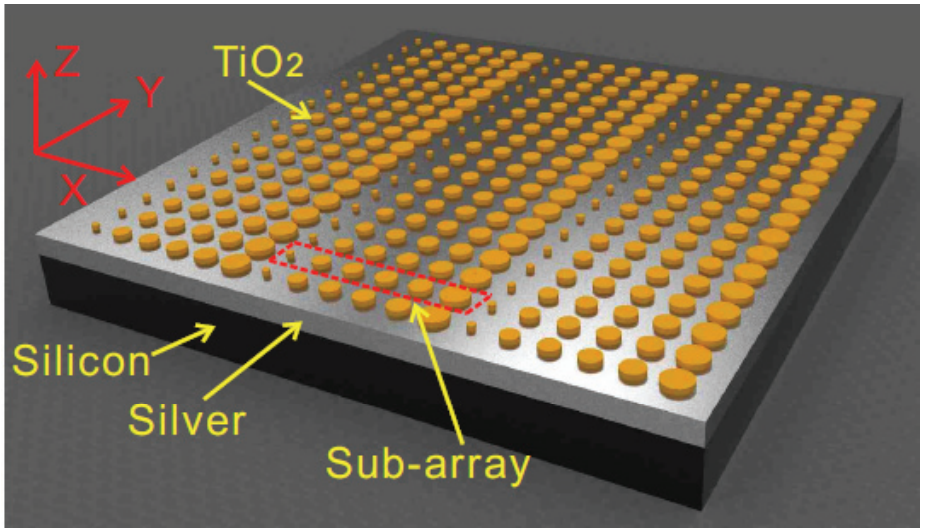
$$sin\theta = \frac{\phi}{kd}$$

6-element sub-array

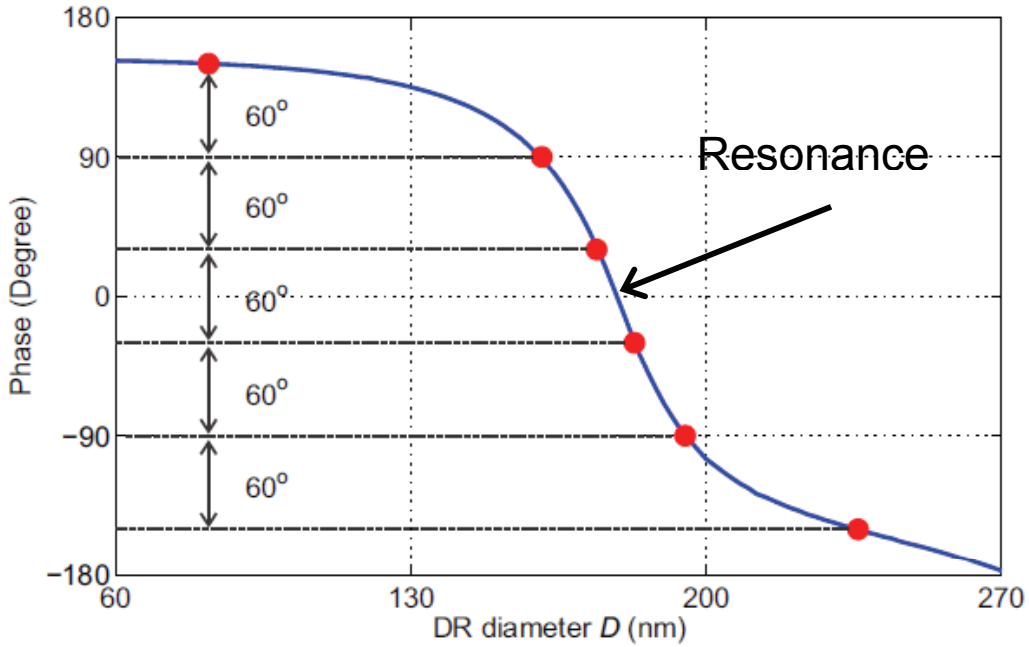
Normal incidence



Simulated scattered E field from a 6-element sub-array



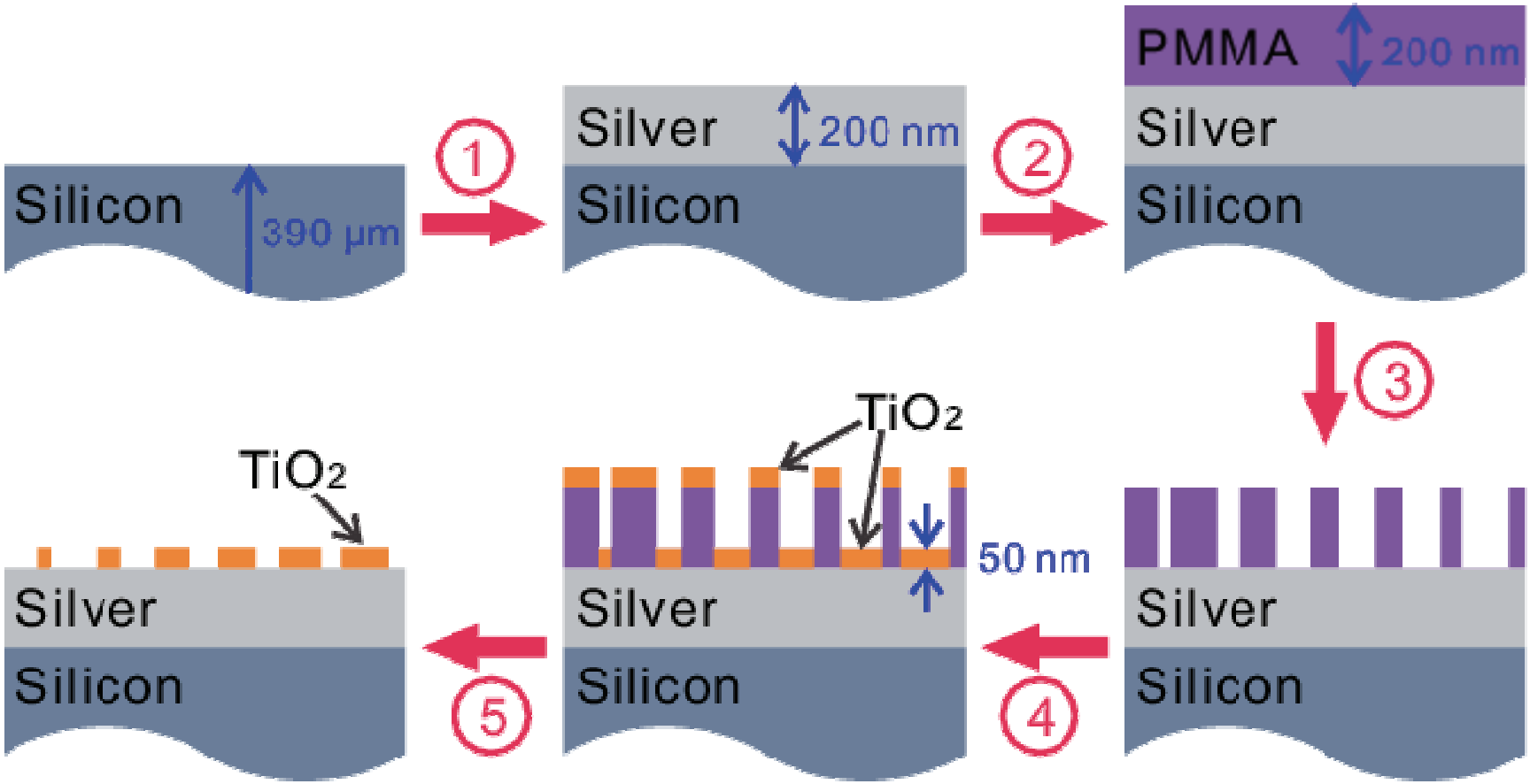
6-element reflectarray



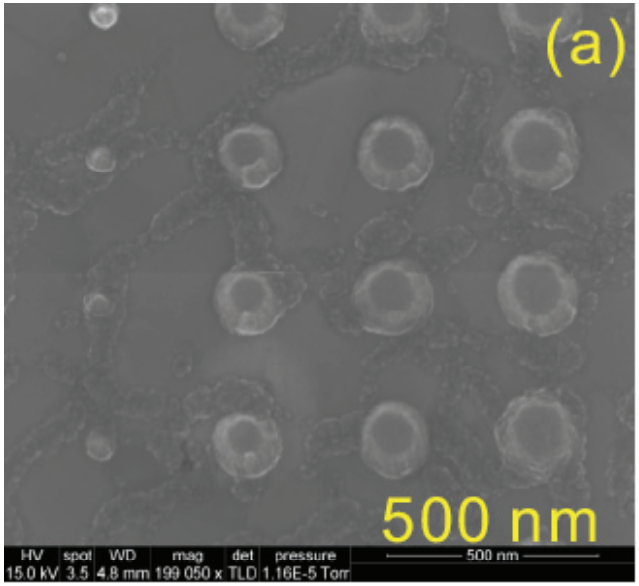
Fabrication

RMIT UNIVERSITY

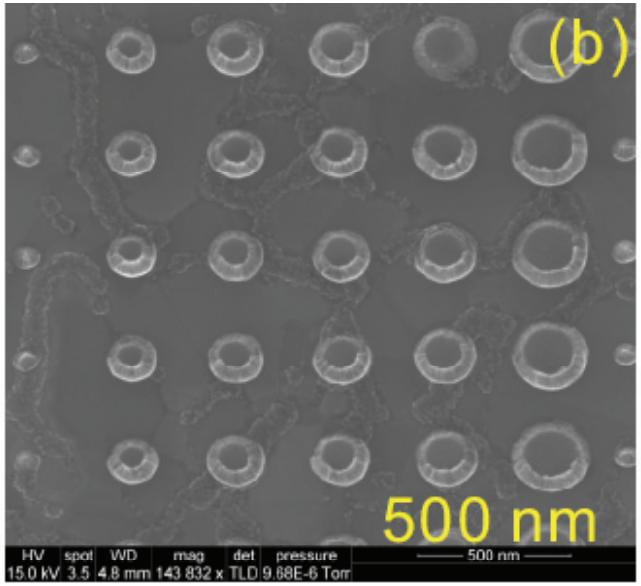
Functional Materials and Microsystems Research Group
School of Electrical and Computer Engineering



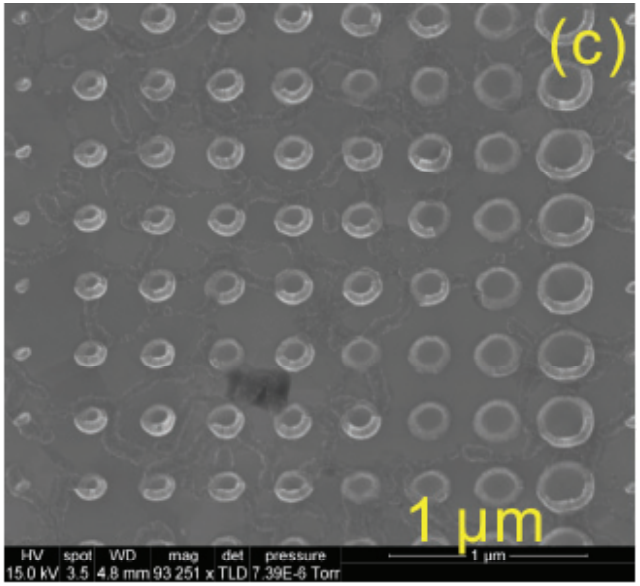
Fabricated samples



4-element reflectarray
Deflected beam angle: 27°



6-element reflectarray
Deflected beam angle: 20°

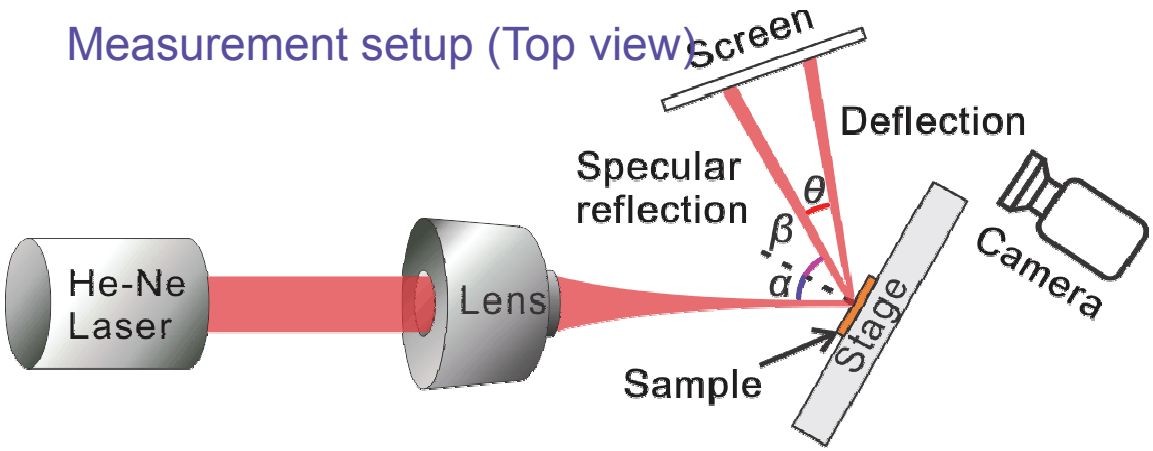


9-element reflectarray
Deflected beam angle: 12°

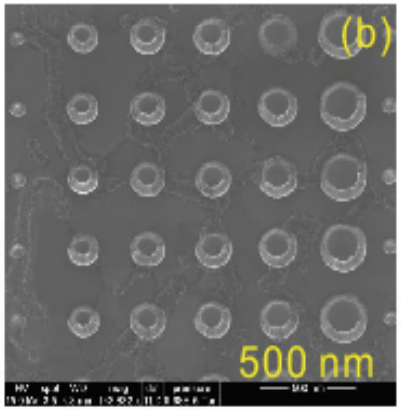
Area: 40 µm x 40 µm
Array: 130 x 130 elements

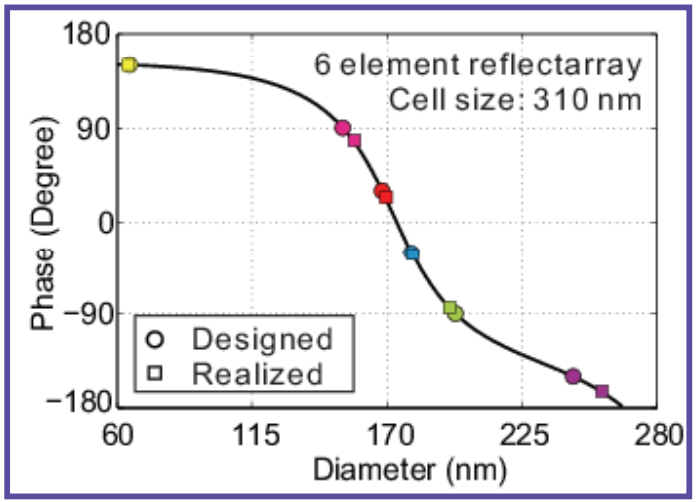
Measurement

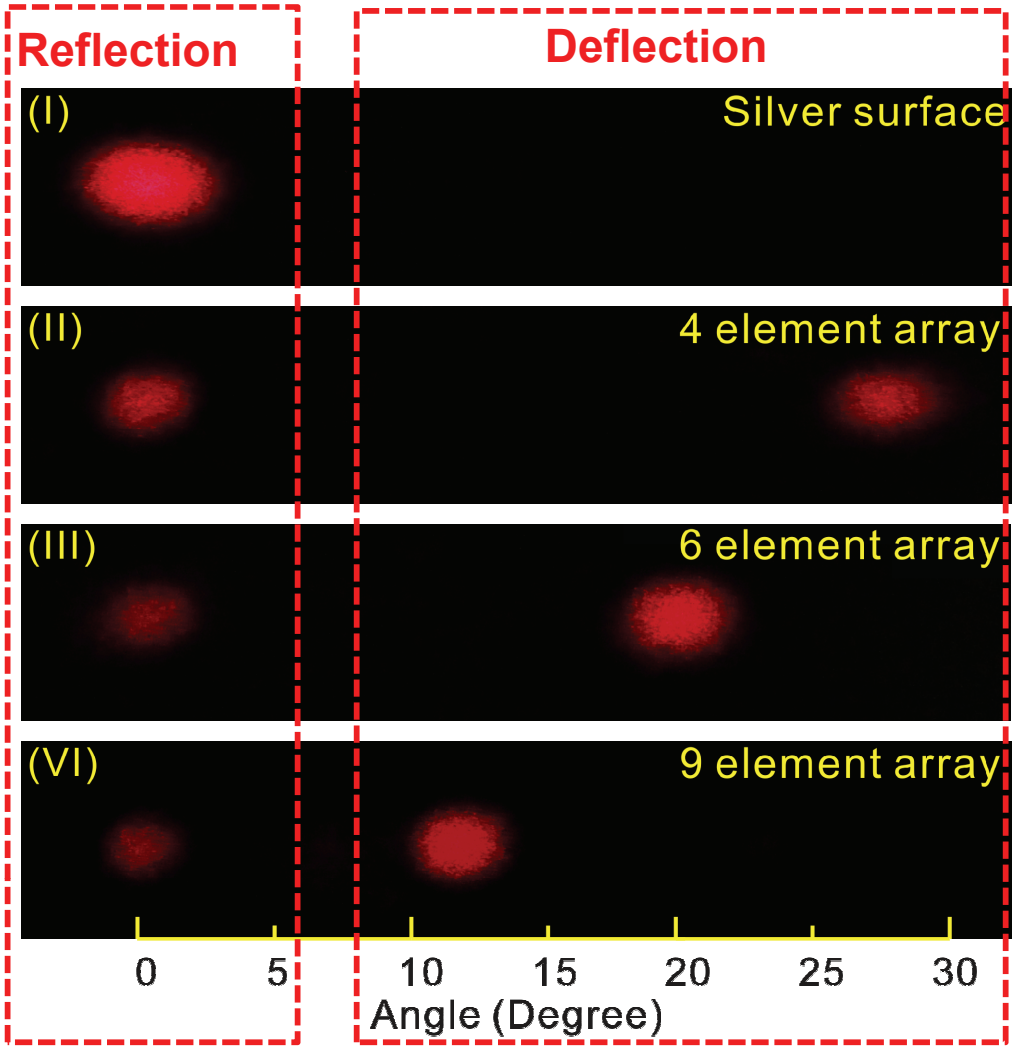
Measurement setup (Top view)



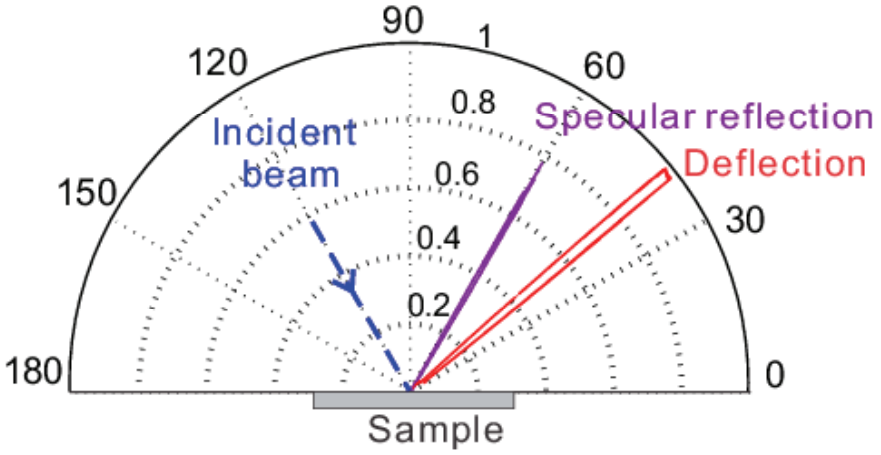
Best sample: 6-element array



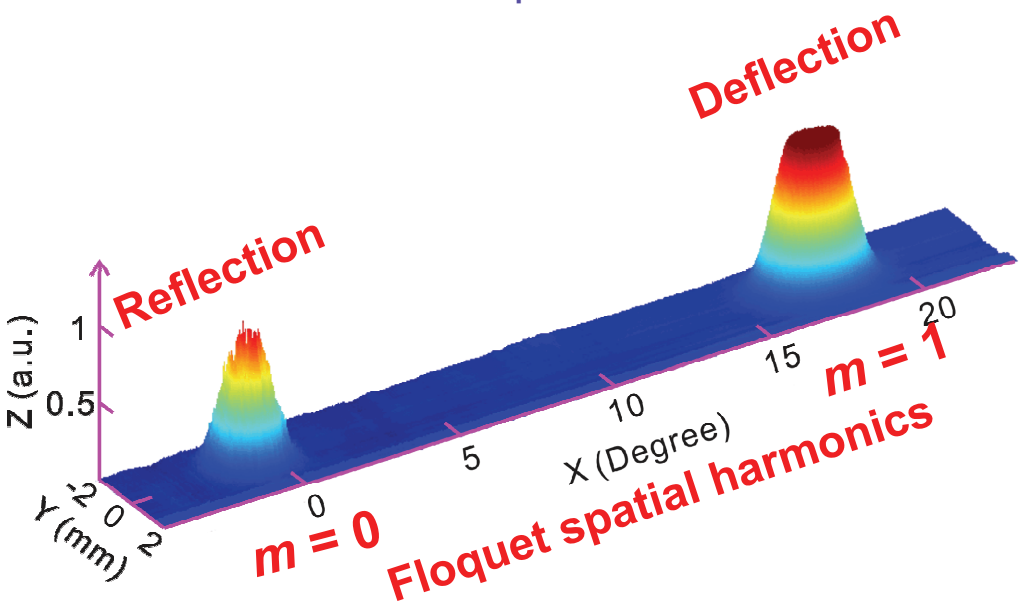




6-element reflectarray

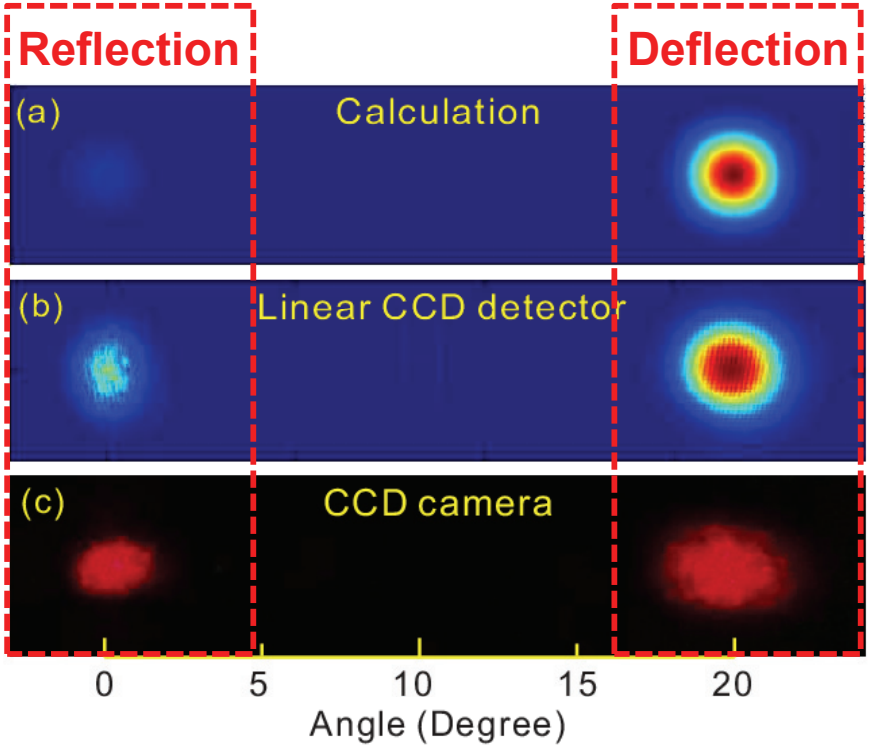


Radiation pattern



3D beam pattern recorded by linear CCD detector

2D Beam pattern



Ratio of specular reflection to deflected power: 1: 4.42

Overall efficiency: 40%

Conclusions

- Scaling of dielectric resonator antennas shows their high efficiency up to the infrared & visible light regimes
- Nano-photonic devices can take inspiration from antennas and benefit from techniques developed in the antenna community

Work in Progress

- Improved Efficiency of optical DRA
- All dielectric antennas
- DRA lens-array
- Cloaking

Acknowledgements

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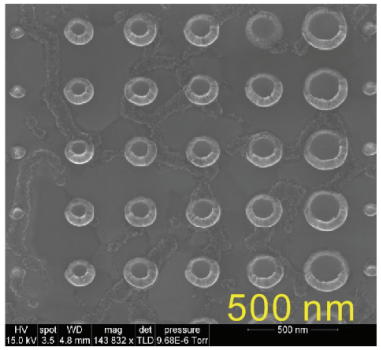
L. Zou et al., “Dielectric resonator nanoantennas at visible frequencies”, Opt. Express **21(**1), 1344-1352 (January 2013)



Thank you for your attention!